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SOUND-GRAPHS: A NUMERICAL DATA ANALYSIS METHOD FOR THE BLIND

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Sound-Graphs: A Numerical Data Analysis Method for The Blind*

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Abstract

A system for the creation of computer generated sound patterns of two dimensional line graphs is described. The objectives of the system are to provide the blind with a means of understanding line graphs in the holistic manner used by those with sight. A continuously-varying pitch is used to represent motion in the x-direction. To test the feasibilty of using sound to represent graphs, a prototype system was developed and human factors experiments were performed. Fourteen subjects were used to compare the tactile-graph methods normally used by the blind, to these new sound-graphs. It was discovered that mathematical concepts such as symmetry, monotonicity and the slopes of lines could be determined quickly using sound. Even better performance may be expected with additional training. The flexibility, speed, cost effectiveness and greater measure of independence provided the blind or sight-impaired using these methods was demonstrated.

1. Introduction

The familiar 2-dimensional line graphs we use in presenting much of our numerical results are an important means for studying the relationships, trends, and characteristics of data collections. We obtain an intuitive understanding of the information contained in numerical data by observing a holistic visual image of the curve. To the visually impaired who are interested in scientific fields of study, difficulties exist due to the visual orientation of the ways used to convey most scientific information. A system to create graphs in sound, or audio images, is described that may provide the blind with a rapid and intuitive understanding of numerical data.

In order to test the feasibility of graphs in sound a set of human factors experiments were carried out on both blind and sighted individuals to determine whether sound could convey the characteristics of the graphs. A prototype system was developed that plays the graphs in 3-second periods of continuously-varying pitch that was intended to follow the outline of an x-y graph. The audio images were compared to tactile-graphs that are engraved in sheets of plastic, from which the blind can feel the curve as a raised line or edge.

Tactile-graphs, one of the few ways the blind currently have to work with curves and graphs, are slow and difficult to use, require considerable time to engrave, and are fairly inconsistent in quality. Computer generated sound can be created quickly and with a high degree of accuracy. If the user has a home computer the method is inexpensive as well.

The results of the experiments showed that individuals rapidly learn to understand sound-graphs and use them more quickly than tactile-graphs. The tactile-graphs were somewhat better among the blind, primarily because of the greater familiarity of the blind with haptic (touch) methods. Nonetheless, with greater use and training sound-graphs will do very well.

2. Previous Methods of Data Description for the Blind

There have been attempts to make tools for analyzing numerical data or mathematical functions available to the visually impaired, especially for teaching purposes. A blind student must accomplish

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many of the same analysis and interpretation tasks others perform when observing a collection of data, such as one created from an elementary physics experiment. Characteristics identified in numerical data are such things as outlying data points, discontinuities, the slopes of lines, and others. Currently the blind student requires the assistance of another individual to help interpret the data. This is done by verbally describing the data or drawing the curve in the palm of the hand. Another method that has been used to describe graphs are raised lines or dots etched into a plastic sheet. Lederman and Campbell [Led80] use the term "tactile graphs" for displays that use raised curves. They performed a series of human factors experiments to test the usefulness of tactile graphs as a means of conveying information such as: "Are these two curves converging, parallel, or diverging?" and "As X increases does this curve increase, decrease, or remain about the same?". They also varied the design of the tactile graphs to include grids on the graphs, and grid overlays and underlays, the last two being separate grid attachments that could be superimposed on the curve or felt from underneath. Their results indicated that tactile graphs could be used successfully to permit the blind to receive information about the characteristics of curves.

Another device, the Optacon reader, made by Telesensory Systems, Inc., [Tel84] is one example of a system that permits a user to independently take any simple written or graphical material and observe its contents. The user of an Optacon scans a page slowly with a miniaturized camera and the regions of varying brightness under the detector are transmitted to a grid of vibrating rods under the fingertip of the user's opposite hand. With this device it is possible to track the shape of an x-y curve.

Although of proven usefulness, haptic methods such as tactile-graphs have many drawbacks such as cost, bulkiness of the materials, and the requirement that the user must have others create the materials. Finally, these methods are slow and require considerable time on the part of the user in order to learn to use them effectively.

3. Sound and Information Transfer

To the blind or sight-impaired individual the avenue of sound provides the main source of information about their environment. Communication with friends and acquaintances, musical enjoyment, and access to printed material on tape via Recordings for the Blind, Inc., are all examples showing the importance of sound to the sight-impaired.

3.1. Sound and the Physiology of Hearing

In the present study, sound has been used to investigate the possibility of transmitting numerical information to a user, relying on the powerful processing capabilities of the human hearing system. The human ear has several characteristics that may be exploited. In particular, our ability to remember pitches or sequences of pitches (notes) is highly developed. Most listeners can differentiate between two pitches varying in frequency by only a very small amount. Saslow demonstrated[Sas67] that pitch discrimination was still very good even when two test pitches near 120 Hz were separated by as little as 0.3 Hz (0.25%). The volume and timing of acoustic signals, as well as the perception of the location in space of the source of sound, is also easily determined by most individuals. In all, it is claimed [Yeu80] that some 20 characteristics of sound can be identified. This is particularly true with respect to tonal music, where such differences as the timber (harmonic content), attack, duration, and decay of notes are often easily perceived.

An advantage sound has over tactile methods is its greater bandwidth as a channel for the flow of information. For example, a typical braille user may read at 50-100 words per minute, whereas speech may be comprehended at speeds from 200 to as high as 400 words per minute.

The frequency range of hearing, 20-20,000 Hz in the very young, is generally not fully utilized by those who are experimenting in the transfer of information in sound, but is restricted to the range of primary sounds of speech, 300-3000 Hz. This restriction is placed on the bandwidth of the sounds for various reasons, such as hardware limitations in sound reproduction, the savings in storage requirements in the computer system memory, and the aesthetically more pleasing nature of sounds in this range.

3.2. Pitch and Vertical Location in Space

One interesting characteristic of hearing is the relationship between the pitch of a tone and the perceived vertical location of the sound source, as investigated by Roffler [Rof67, Rof68a, Rof68b]. There appears to be a natural tendency, even in infants, to perceive a pitch that is higher in frequency to be coming from a source that is vertically higher in space when compared to some lower tone. In the present study, variations in the amplitude or y-direction of an x-y data collection were mapped into corresponding increases and decreases in pitch. This natural psychoacoustic phenomena lends support to the appropriateness of using a higher pitch for a larger y value.

3.3. Pitch Response of Human Hearing

The response to external stimuli of most of the body's sensory organs is logarithmic in nature, and the same is true with our perception of pitch. The term "psychological distance" [Mat69a] is used to describe the relative scaling of psychological stimuli and was investigated by Stevens et al. [Ste37]. In their study they requested that subjects choose a pitch that appeared to them to be half as high as that of a given reference pitch. By repeating this procedure over the range of hearing they developed a curve (see Figure 1) indicating the perceived relationship of pitches to one another. The unit called

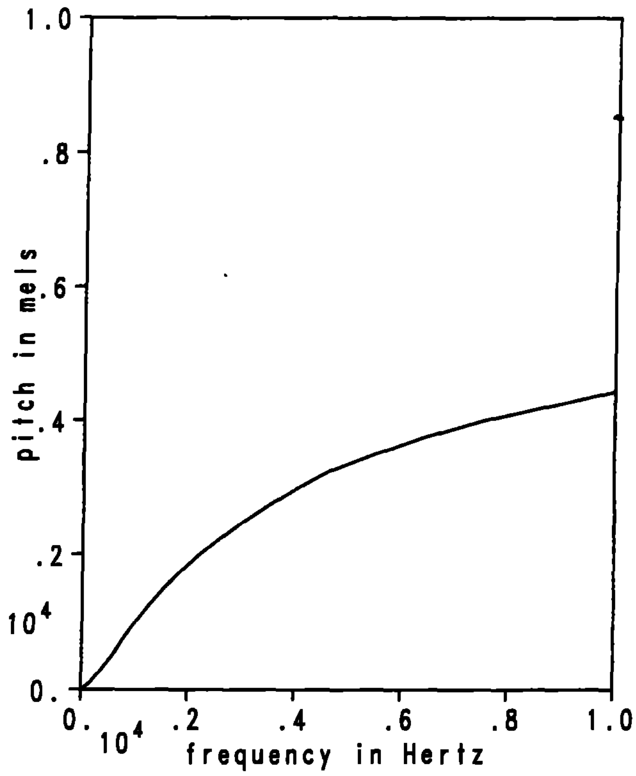

Figure 1. Relationship between the perceived linear scale (in mels) and the required output frequency (in Hz).

"mels" was used in this respect to represent a scale on which an increase in frequency is heard as a correspondingly linear increase in pitch to a human listener.

The frequency of 1000 Hz was chosen by Stevens et al., as the reference point where both scales would have the same value (1000 Hz = 1000 mels). Above and below this point the halving or doubling of perceived pitches were mapped to corresponding actual frequencies. Notice that in the critical range of 200 to 1500 Hz the response is nearly linear. However, as higher pitches are required it is necessary to provide frequencies in an exponentially increasing manner.

It is important to note potential problems with use of sound as a technique for transmitting numerical data. Certain individuals may have little perception of pitch, or have a "tone deafness," due to hearing loss in certain frequency bands or a lack of musical training and experience. Environmental noise may also mask the perception of sound [Mat69b], particularly at higher frequencies. This implies that the environment where audio images are to be used should be relatively free of auditory distractions.

4. Previous Work with Sound and Numerical Information

Prior to the advent of general computer systems capable of electronically synthesizing sounds on demand, little work was done to use sound for data transmission. One interesting attempt was a modification of an oscilloscope [Ald79] for the blind such that the waveforms would be translated into sound. An increasing pitch represented an increasing voltage being displayed on the screen.

Computer systems provided a number of significant advantages for exploring sound techniques. A data collection or mathematical function may be rapidly translated into some changing sound pattern, that in turn may be modified at will. A properly designed computer interface using good techniques of human engineering requires little or no assistance from outside individuals. The blind user must be capable of controlling the system via keyboard, joystick, "mouse," or other means. Recently the cost of personal computers has declined to the point where they are affordable to the blind. Many of the current microcomputers come with sound enhancements and the software for synthesizing music. We may expect to see even more advanced sound systems on microcomputers in the future.

Prior work in sound for numerical data analysis has been undertaken in only a few instances. The work of Sara Bly [Bly82] was significant in that an attempt was made to allow users to analyze multi-dimensional data collections. Joseph Mezrich [Mez83] has looked at enhancing visual displays with sound, especially for analyzing time series data involving oil well log data and economic patterns.

Both Mezrich and Bly relied upon discrete musical tones or notes to transmit their information. The present project uses changing values of the y-axis information as continuously changing pitch. The relative merits of continuous versus discrete forms of encoding are worth exploring. Western music (i.e., tones and chords on the even-tempered scale) is familiar and acceptable to most listeners. However, placing listeners into a new frame of reference with respect to sound, and retraining their ears to a new (linear) scale, may enhance their ability to form a clearer mental picture of the data being presented. Using discrete notes on the even-tempered scale has another disadvantage in that there is a severe restriction on the number of increments or steps that can be used to represent the data. Mezrich used 22 notes on the major scale because of its pleasing "upbeat" qualities, but a system using continuously changing pitches may have the equivalent of hundreds of such steps to choose from.

5. Creation of Sound-Graphs

5.1. Computer System Hardware

All development work was done on a Three Rivers Perq Model I stand-alone computer system having 1-Mbyte of internal memory and a 24-Mbyte Winchester technology disk drive. A bit-mapped display with 1024 × 768 resolution was available, however, the most important system feature was the presence of the Motorola MC3417 integrated circuit and associated hardware, which is designed for encoding and decoding audio information. This device uses the CVSD (Continuously Variable Slope, Delta modulation) data compression technique used frequently in the voice-band telephone communication industry. By supplying this device with a carefully constructed bit-stream at 32,000 bits/second, a fairly accurate reproduction of any desired sound can be generated within the approximate range of 160 to 1500 Hz. This frequency range corresponds roughly to that which Yonezawa and Ito [Yon77] found optimal (200-2000 Hz) in their experiments with a "display panel" they created using sound. The CVSD encoding scheme is more accurate and thus introduces less noise at lower frequencies, although much higher values of pitch can be obtained.

5.2 Software Development

At this point only a prototype system has been completed. The system as it now exists will take a table of x-y pairs and translate them into a complete sound-graph in less than 90 seconds. This allowed us to do the human factors testing described in the next section. A system overview is shown in Figure 2 that details the major steps involved in producing a sound-graph.

5.2.1. Data and Data Format

The source of x-y data could be a mathematical function, a collection of data points designed to demonstrate some mathematical concept, or the results of an experiment. The set of (x,y) pairs must be stored in a simple sequential file on disk for subsequent preprocessing. Disk storage requirements were not excessive, and the sound image was of sufficiently high quality.

5.2.2. Rescaling, Relocation, and Linear Pitch Correction

The data points are mapped linearly into the range 0.0 to 3.0 corresponding to the three second time duration used in the playback. The y values are rescaled so that they fall into the range of values corresponding to the maximum and minimum pitches attainable by the system hardware. Both rescaling and relocation are done using linear interpolation.

The term *mels* is used to describe the perceived linear pitch scale as adapted from Stevens et al. [Ste37] (see Section 3.3). An arbitrary decision was made to arrive at values on this scale via the function:

$$\text{mels} = (200.0 * y) + 200.0 \quad ,$$

and it was hoped that linear changes in mels would be perceived as equivalent linear pitch changes.

5.2.3. Computation of the Output Sine Wave

An efficient method often used for computing the sample points of an output sound wave in computer-generated music is described by Bateman [Bat80], and was included in the present system. The goal is to produce a series of numbers corresponding to the changing amplitude of the desired sound pressure wave. A look-up table containing 1000 data points describing one full cycle of the desired output is used. This table is created only once and can specify the shape of a pure sine wave (as used in the prototype system) or some other arbitrary periodic sound pattern such as that generated by a particular musical instrument. The current software system permits the substitution of some other waveform.

When it is necessary to produce a specific pitch via the computer, this waveform table is sampled at equally-spaced intervals at the

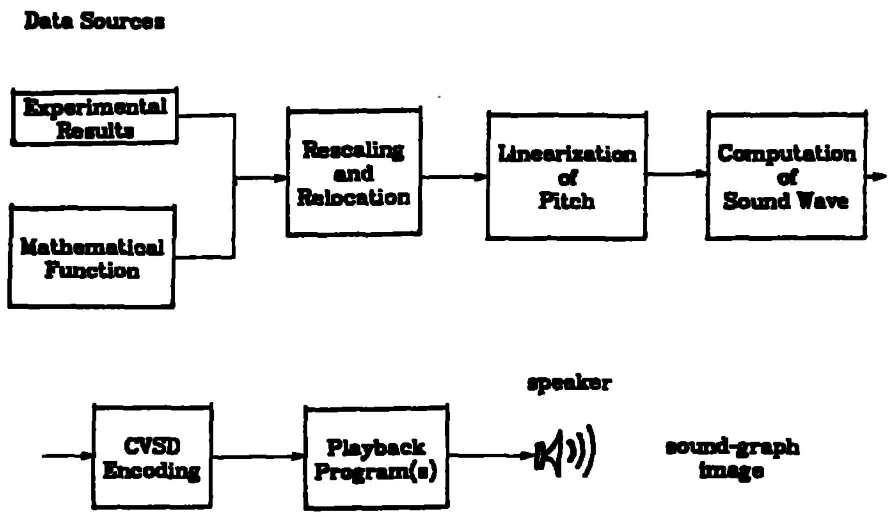

Figure 2. System overview. The steps shown above are those required to produce the sound-graph.

appropriate rate, reproducing a good equivalent to the desired wave shape. Since these equally-spaced intervals may not fall precisely on locations where data values are present (i = 1, 2, 3, ..., 1000), linear interpolation is used to approximate the value.

Although the prototype system uses a pure sine wave with no significant harmonic content (at least at lower frequencies), we would like to experiment with tones that are richer and have a more pleasing and natural sound. Modifying the timbre or harmonic content to more closely approximate a musical instrument is relatively simple. Care must be taken, however, not to spread the pitch over too wide a range, giving rise to problems with determining the central pitch of the sound signal. Shepard, in fact, reported [She64] that certain tones with complex harmonics could have very ambiguous positions on a linear pitch scale, so some experimentation is required.

As the data points describing the sound waveform is assembled the CVSD encoding scheme is used to compress the data into the bit-stream required by the Perq output hardware. The 16-bit integers were thus translated into a series of 1-bit values, greatly reducing the storage and input/output processing requirements of the system.

5.2.4 Playback Options

A number of playback options are available for hearing the finished results. For example, it is useful to be able to hear a sound-graph played rapidly a number of times, or on other occasions hear a curve played in an alternating fashion with some well-known reference sound-graph. These and other playback methods were tested to determine the listening techniques that would be most helpful in conveying the information present in curves.

5.2.5. Audio Cues for Secondary Information

A full sound-graph system would contain timbre control to convey some secondary aspects of the x-y curve, such as its first derivative. By adding more overtones to the sound as the first derivative increased, a better feeling for the rate of change of the curve might be perceived. Alternatively, the first derivative might be played back using a different frequency range so that it may be heard simultaneously with the primary curve.

A number of characteristics of graphs that are easy to compute are to be added to the sound-graphs in the form of a set of audio-cues. For example, the points where the global maxima and minima are to be marked with a special signal tone, thus highlighting their location. Still other audio cues are planned for such places as the inflection points, discontinuities in the curve, or the point which the curve crosses some y-value of particular interest.

Just as the common graphics packages available on most computer systems today have a number of tools to manipulate curves, so too should an equivalent system for the blind. For example, automatic rescaling of the data to fit the audio "frame-of-reference," zoom-in and zoom-out capabilities, and the ability to smooth the original data should be available. We have not yet determined which interface devices will control these actions.

Part of the projected sound-graph system is a library of reference curves having known characteristics. It should be possible to rapidly compare an unknown curve against one or more known curves. Only small modifications of the present software are required to do this. More human factors testing should be done to understand how the user may best hear these differences.

6. Human Factors Tests on Sound-Graphs

Our prototype system was tested by human factors experiments in order to assess the feasibility of a more elaborate sound-graph system.

6.1. Experimental Methods

A set of experiments were carried out to assess the relative effectiveness of sound versus tactile methods in conveying x-y data. Of major interest was whether blind or blindfolded subjects could make the same judgements about line graphs that are commonly made by sighted individuals. Some of the characteristics observed when viewing curves are such things as the relative slopes of lines, the general class of a curve (e.g., exponential), and the presence of symmetry. These and other features were selected to form a set of tests to determine if one method was faster, more accurate, or more suitable for conveying particular curve characteristics than another.

The experiment was divided into two portions in which the subject was tested using one method of presentations (e.g., tactile) and then retested using the second method. Because the two test portions were identical in content all subjects were randomly distributed as to which method they were exposed to first, in order to counteract possible learning effects. Within the test there were five sets of test questions, each designed to measure the discrimination of one curve characteristic. The order of presentation of these test sets were randomized to further counter-balance any learning improvements as the test progressed.

Before beginning the experiment each subject was interviewed to determine his background concerning visual or tactile defects, mathematical training, musical experience, age, and other factors.

6.2. Sound-Graph Tests

Before starting the sound portion of the experiment each subject was tested for their ability to hear differences in pitch. This pitch test also served to test the quality of the sound produced by the system.

In both the sound and tactile portions of the experiment a measure was kept of the overall time it took the subject to do the tests. These simple time measurements combined both the time for training and testing the subject into a single value so the relative measure of speed of each method of presentation could be made.

To familiarize the subject with sound-graphs and make certain he or she understood the mathematical concept being tested in each of the five test sections to be described below, the individual was trained on two to four sample curves before each test.

The sound test were:

Test 1: Slopes of lines.

The determination of relative slopes of lines was tested. To test the ability to hear the various slopes of lines the subject was presented with pairs of straight lines, each having a slightly different slope.

Test 2: Straight lines versus exponentials.

The test involved asking whether a given curve was one or the other of these two types.

Test 3: Monotonicity.

This test involved the discrimination of the tendency of a curve to behave monotonically, either ascending or descending. The monotonic curves were not necessarily strictly monotonic.

Test 4: Convergence.

Some curves exhibit convergence or the tendency to approach some limiting value. Discrimination of this form required that the individual predict the future behavior of the given curve.

Test 5: Symmetry.

Another curve discrimination skill that is useful is the ability to detect symmetry about some vertical axis. Curves with various degrees of symmetry were presented.

6.3. Tactile-Graph Tests

In the tactile portion of the experiment the curves were identical in the shape to those of the sound portion except for minor modifications. For the tactile graphs the curves were formed by placing mylar sheets of plastic on a special tablet having a soft writing surface. Each curve was traced using a standard ball point pen, leaving behind a rough line or ridge in the plastic that could be easily felt by the fingers. A frame of reference that was found to be beneficial to the users was provided by creating an x- and a y-axis using double lines spaced 2 to 3 mm apart.

The majority of curves began at the y-axis so that it would be easier for the user to locate the start of the curve. All sighted individuals were blindfolded for this portion of the experiment. Before the commencement of each test each subject was given time to become familiar with some sample curves related to the question at hand.

7. The Results of the Human Factors Tests

A total of 14 subjects were tested in the experiments, 7 of whom were totally blind or legally blind. The average age was 38, with 79% males, 21% females, and 36% of the subjects were college students. Several of the blind subjects were employed as machinists or electrical technicians. All subjects appeared to have sufficient mathematical skills to understand the questions.

The results of the experiments are shown in Figure 3. The overall accuracy was 88.3% using tactile-graphs and 83.4% using sound-graphs, with a statistical difference between the two methods ($p = 0.05$). The similarity in overall accuracy implies that the two methods are comparable in accurately conveying numerical information—although for some kinds of information, one method may have some advantages over the other. No significant difference was found between the number of correct responses for the blind and sighted individuals.

One very promising result, which indicates a continued development of sound-graphs is important, is the speed with which subjects make their determinations about curves. The recognition of curves using sound appeared to be faster, especially for certain kinds of recognition tasks. Occasionally a single exposure to one of the 3-second sound-graphs was sufficient for a subject to give an accurate response, whereas some tactile-graphs required from one to several minutes of manipulation. An estimate of the overall time to perform both training and testing of each subject showed that the tactile half of the experiment took 26.2 minutes whereas the sound portion took only 19.3 minutes on the average.

The tactile-graphs required the users to develop individual exploration methods. It is important to develop additional exploration techniques with sound as well. One such technique utilizes the zoom or expanding feature.

8. Conclusions

In this paper we have described a system that translates line graphs into audio images we call sound-graphs. A prototype system has been developed using a pure sine wave to generate the sound. A complete sound-graph system would contain different timbre controls to convey secondary aspects of the curves. Audio cues marking maxima, minima, discontinuities, and grid points will provide more information for the listener. Zoom features will allow more individual exploration of the graph. A library of well-known curves would provide the users with a standard set of references. The presentation of multiple curves is now possible but its use needs to be explored and tested.

The results seems to indicate that sound and tactile methods have their own unique advantages and disadvantages, but the speed, flexibility, and fuller understanding provided by sound-graphs strongly recommend their further development. Sound-graphs have the ability to free the user's hands for other tasks, and more importantly, they can be used effectively regardless of the individual's orientation or distance from the source of sound. Clearly individuals were able to learn rapidly to interpret these new sounds in a meaningful way.

Number of Correct Responses												
	Test No. 1		Test No. 2		Test No. 3		Test No. 4		Test No. 5		Total	
ID's	T*	S*	T	S	T	S	T	S	T	S	T	S
1	4	5	4	4	4	4	4	4	3	2	19	19
2	5	4	4	3	4	4	4	3	3	3	20	17
3	6	5	2	2	4	4	3	4	2	4	17	19
4	6	5	4	4	4	4	3	3	4	1	21	17
5	2	5	4	3	4	4	4	2	4	4	18	18
6	3	5	4	3	4	4	4	3	3	3	18	18
7	3	5	4	2	4	3	4	4	4	4	19	18
8	6	6	4	4	4	4	4	3	4	3	22	20
9	5	4	4	2	4	3	3	3	2	4	18	16
10	6	5	4	4	4	4	3	1	4	3	21	17
11	5	3	4	4	3	4	4	4	4	4	20	19
12	5	5	4	4	4	3	3	3	4	4	20	19
13	6	4	4	4	4	4	4	4	3	4	21	20
14	4	5	4	4	3	4	3	4	4	3	18	20
$\bar{x}$	4.71 79%	4.71 79%	3.86 96%	3.36 84%	3.86 96%	3.78 95%	3.57 89%	3.21 80%	3.43 86%	3.29 82%	19.43 88%	18.35 83%

* T = tactile, S = sound.

Figure 3. Results of the experiments.

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